CBN Gear Grinding — A Way to Higher Load Capacity?

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Abstract

Because of the better thermal conductivity of CBN abrasives compared to that of conventional aluminum oxide wheels, CBN grinding technology promises a "cooler" grinding process, which induces residual compressive stresses into the component, and possibly improves the subsequent stress behavior. This thesis is the subject of much discussion. In particular, recent Japanese publications claim great advantages for the process with regard to an increased component load capacity, but do not provide further details regarding the technology, test procedures or components investigated. This situation needs clarification, and for the this reason the effect of the CBN grinding material on the wear behavior and tooth face load capacity of continuously generated ground gears was further investigated.

Introduction

The further development of the technology for gear grinding is aimed at both increasing productivity and efficiency and achieving product optimization. CBN grinding technology, i.e., grinding with abrasives of cubic boron nitride, promises to meet both requirements. CBN allows one to increase the cutting speed and, at the same time, increases the tool life. Because of the high thermal conductivity of the abrasive, CBN offers greater safety against thermal damage to the tooth flanks (Ref. 1).

As already established by G. A. Johnson (Ref. 2), CBN wheels grind "cooler" than conventional aluminum oxide wheels, because of the better thermal conductivity of the CBN abrasive, which improves the subsequent stress behavior of the components.

Japanese publications (Ref. 3) assert that the use of the CBN grinding technology for finishing gears increases the strength properties by about 30%. This would make it possible to reduce the size of gears by approximately 30% while maintaining the same load capacity of the gear elements. There is, however, no exact technical data or information on the conditions under which the investigations were performed, so that it is not possible to compare or assess the results.

On the other hand, American publications (Refs. 4 & 5) conclude that the CBN grinding technology for gear finishing does not improve the load capacity, but is preferred to conventional aluminum oxide grinding because of its improved process safety.

This contradictory information was the reason for investigating the influence of CBN abrasives on the face load capacity of continuously generated ground gears.

Test Program and Grinding Parameters

Spur gears manufactured using the continuous generating grinding method (Ref. 6) were used for the tests. To cover the subject "surface load capacity of gears" as comprehensively as possible, the surface zone was investigated for the progress of wear by measuring residual stress and profile deviations. The following grinding materials were used for finishing the gears:

Table I — Test Program and Grinding Parameters

		Aluminum Oxide Multi-Pass Grinding	Aluminum Oxide Shift Grinding		Galvanically Plated CBN Multi-Pass Grinding, Roughing	Galvanically Plated CBN Multi-Pass Grinding, Finishing	Vitrified Bond CBN Multi-Pass Grinding Used Grinding Wheel	Vitrified Bond CBN Multi-Pass Grinding Newly Dressed Grinding Wheel	
		Variant 11	Variant 12	111	Variant 21	Variant 21	Variant 31	Variant 41	46
Residual Stress	σ_E	X	X	—	—	X	X	X	—
Load Capacity	σ_H	—	—	X	—	—	—	—	X
Total Infeed Amount	mm	0.60	0.60		0.42	0.18	0.60	0.60	
Roughing Infeed Per Pass	mm	0.02	0.24		0.42	0.02	0.3/0.1/0.1	0.02	
Finishing Infeed Per Pass	mm	0.02	0.04		—	0.02	0.1	0.02	
Roughing Feed Rate	mm/rev	1.60	1.00		0.75	1.40	1.0/1.6/1.6	1.40	
Finishing Feed Rate	mm/rev	0.80	0.85		—	0.70	0.50	0.60	
Grinding Wheel Speed	RPM	1,900	1,900		1,900	1,900	1,900	1,500	

Utilized Grinding Wheels: Aluminum Oxide: 64 A 80/100 F8V
Galvanically Plated CBN: B91
Vitrified Bond CBN: B64...126/V100...150

1. Conventional aluminum oxide grinding medium (64 A 80/100 F 8 V);

2. Galvanically plated CBN (grit size B91 in accordance with FEPA); and

3. Vitrified bond CBN (grit size B64–B126, concentration V100–V150, per FEPA).

The aluminum oxide shift grinding variant (Table I) was used as a reference for the test results from the galvanically plated CBN and vitrified bond CBN variants. Unlike the case of multi-pass grinding, during shift grinding the work piece is offset with respect to the grinding wheel by using the shift axis, so that the grinding wheel is always grinding with a freshly dressed section. This makes the process significantly more efficient and far safer.

The test gears were case-hardened spur gears made of 16 MnCr5E material.

The gears for the aluminum oxide shift grinding variant were finished as reference items using the given grinding data (Variant 12). According to the grinding machine manufacturer (Ref. 6) these parameters are applicable for finishing under production conditions. The multi-pass grinding variant (Variant 11), for which the rough and finish grinding infeed amounts are small, was designed to demonstrate the extent to which the aluminum oxide grinding medium influences the conditions of the material with the small amount of heat introduced.

All the CBN ground gears were produced using the multi-pass grinding method. For galvanically and vitrified bond CBN grain, the finish grinding infeed amounts selected were also very small, as they were with the aluminum oxide, in order to obtain a direct comparison of the grinding medium with regard to the effect on the surface zone. To minimize the introduction of heat, the rotational speed of the grinding wheel was reduced for the vitrified bond CBN grinding wheel (Variant 41).

The technological parameters selected for grinding with the CBN grinding wheel enabled an optimum working result to be achieved and, therefore, fully exploited the advantage of the CBN grinding medium. Compared to this, the settings chosen for the aluminum oxide variants were those typically used in production, but not the ones which produce the optimum results, particularly with regard to the roughness of the tooth faces.

The following is a summary of the most important results of the investigation.

High Residual Compressive Stresses on the Surface Using CBN

Knowledge of the residual stress is particularly important for gears because the component stress results from superimposing load and residual stress. The presented measured results were obtained by radiography

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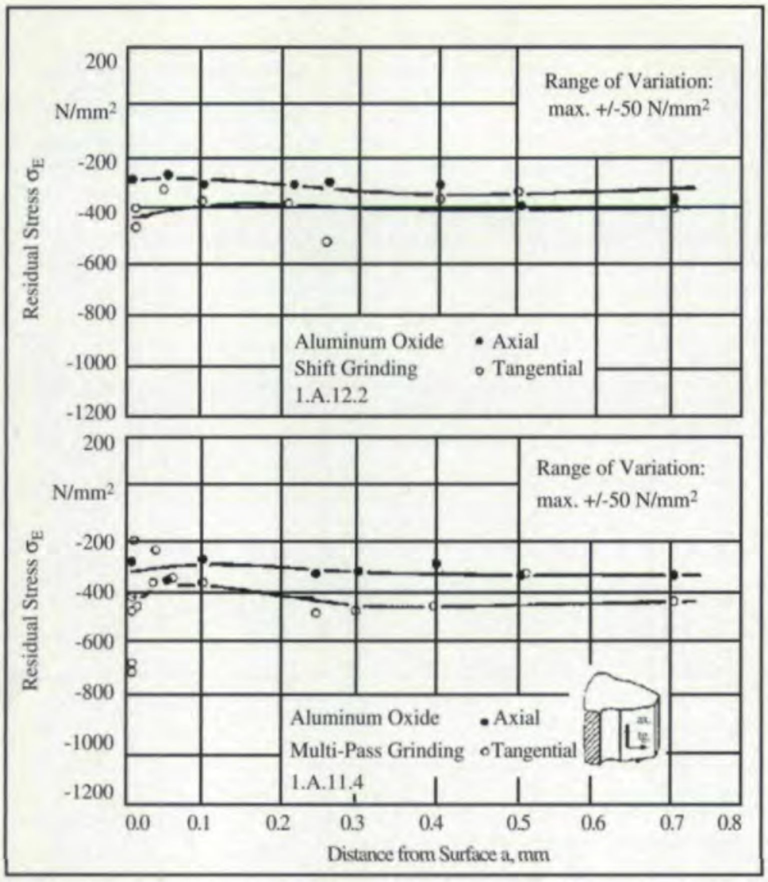

Fig. 1 — Residual stress pattern in the surface zone of the variants shift grinding aluminum oxide (Variant 12) and multi-pass grinding aluminum oxide (Variant 11).

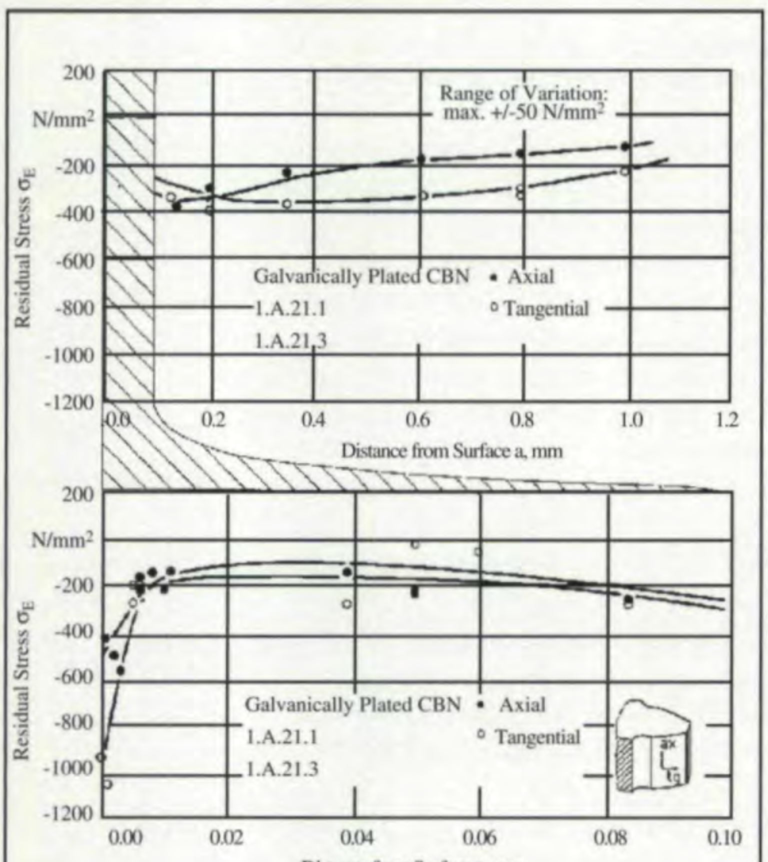

Fig. 2 — High residual compression stresses in the surface zone of gears ground with galvanically plated CBN wheels.

using the $\sin^2\psi$ method (Ref. 7) (211 level, Cr-Kα radiation, 35 kV/35 mA, $2\theta = 156°$). The residual stress patterns in the surface zone of the aluminum oxide ground reference variant are shown in Fig. 1. For gears of Variant 11 (aluminum oxide multi-pass grinding) and Variant 12 (aluminum oxide shift grinding), the tangential residual compressive stresses on the surface were approximately -400 N/mm². The axial residual compressive stresses were somewhat lower, approximately -260 N/mm² on the surface.

The axial and tangential residual compressive stresses are almost the same on the surface for both variants. Overall, the residual stress pattern of both variants showed no significant influence by temperature in the surface zone because of the grinding process. Normally, if too much heat were introduced, residual tensile stresses on the surface would result. This confirms that in this case no deterioration of the surface zone influence occurred, even under normal production grinding conditions (shift grinding, Variant 12) using the conventional aluminum oxide.

For the gears of Variant 21 (galvanically plated CBN, multi-pass grinding), as shown in Fig. 2 the tangential residual compressive stresses on the surface were approximately -950 N/mm². The axial residual compressive stresses were somewhat lower, approximately -500 N/mm² on the surface. These values dropped very quickly to approximately -200 N/mm² at depths greater than 0.01 mm. Overall, the residual stress pattern revealed no temperature influence in the surface zone because of the grinding process. The high residual compressive stresses resulted from plastic deformation during the contact between the grinding wheel and the tooth face. The lower diagram in Fig. 2 shows clearly that the effect did not penetrate any further than 10 µm.

Two vitrified bond CBN variants were used: vitrified bond CBN with a newly dressed grinding wheel (Variant 41); and vitrified bond CBN with a used grinding wheel (Variant 31). The used grinding wheel with the vitrified bond CBN had already been used once before this grinding process and was not dressed for this particular application. A large infeed amount was chosen for finishing.

Fig. 3 shows the residual stress patterns in the surface zone for both variants. For the vitrified bond CBN variant with a used grinding wheel, the tangential residual compressive stresses on the surface were approximately -1000 N/mm². The axial residual compressive stresses were approximately -500 N/mm². In this case again there was a rapid drop of the stress values with increased depth to about -300 N/mm².

The residual stress pattern of the CBN variant with the used grinding wheel was somewhat different from the vitrified bond CBN variant with the newly dressed grinding wheel. In this case the tangential residual compressive stresses on the surface were only about -400 N/mm² and the axial compressive stresses were approximately -300 N/mm². These somewhat lower residual compressive stresses were possibly the result of the influence of the re-hardened zones which have a negative influence on the measured results.

Overall, high compressive stresses were found after CBN grinding even with high infeed amounts. The affected depth was very small (about 10 µm), and the stresses did not penetrate as deep as those resulting from sliding and rolling on the tooth faces.

Surface Roughness Measurements

The recordings of the roughness measurements in Fig. 4 show that the variants, aluminum oxide with multi-pass grinding or aluminum oxide with shift grinding, produced a higher roughness than the vitrified bond and galvanic plated CBN variants. It should be pointed out, however, that the roughness depth on the CBN ground gears at discrete points (for example, in the range of the 1 mm measuring length for galvanically plated CBN) deviated greatly from the average roughness R_z. This deviation also resulted in a substantially higher value for the maximum roughness R_t. It may have been caused by a protruding CBN grit. Indications of this were the ridges which appeared on the right and left and which were very similar to the plastic deformation caused by contact with the grit.

Under EHD conditions (complete separation of the metal surfaces through the elasto-hydrodynamic pressure build-up in the lubricant film) these ridges cause metallic micro-contacts of both tooth flanks which result in high micro-Hertzian stresses and

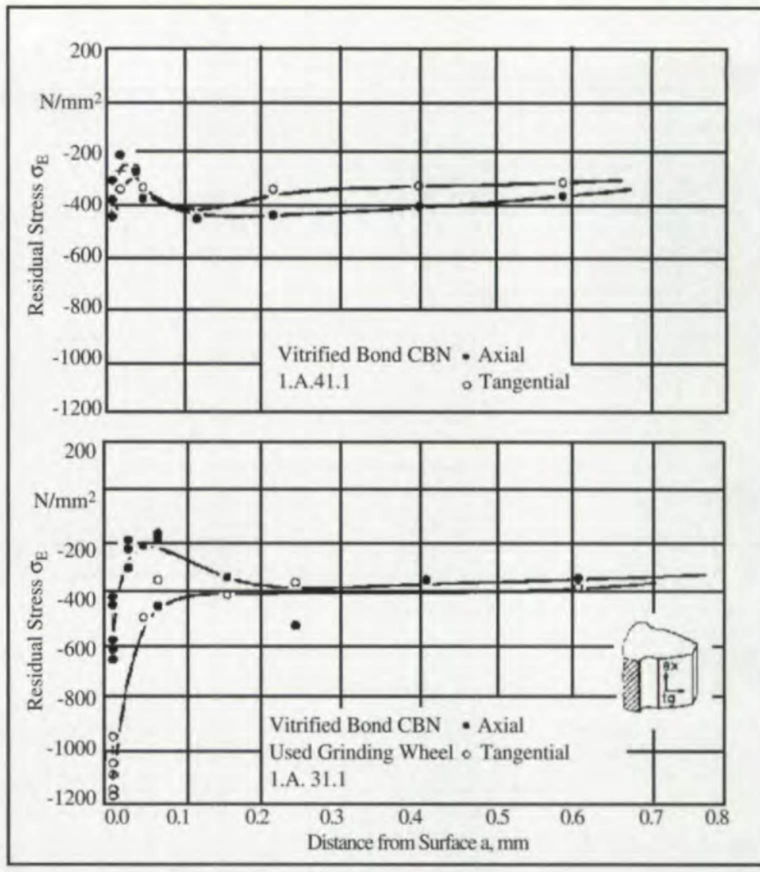

Fig. 3 — Residual stress pattern in the surface zone of gears ground with vitrified bond CBN wheels; used grinding wheel (Variant 31), newly dressed grinding wheel (Variant 41).

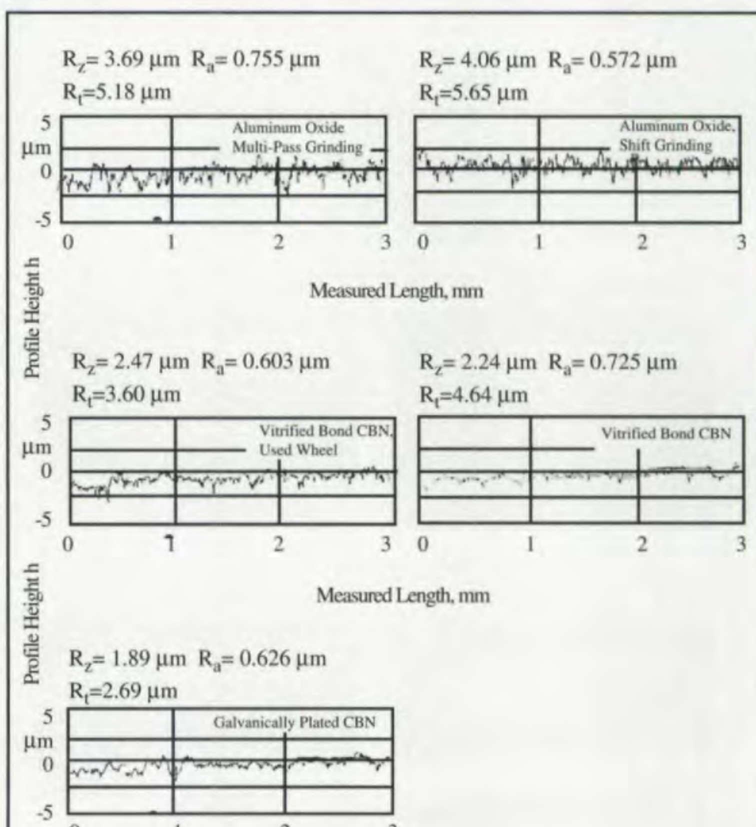

Fig. 4 — Recordings of roughness measurement of the ground surface of the tested gear variants in the initial state.

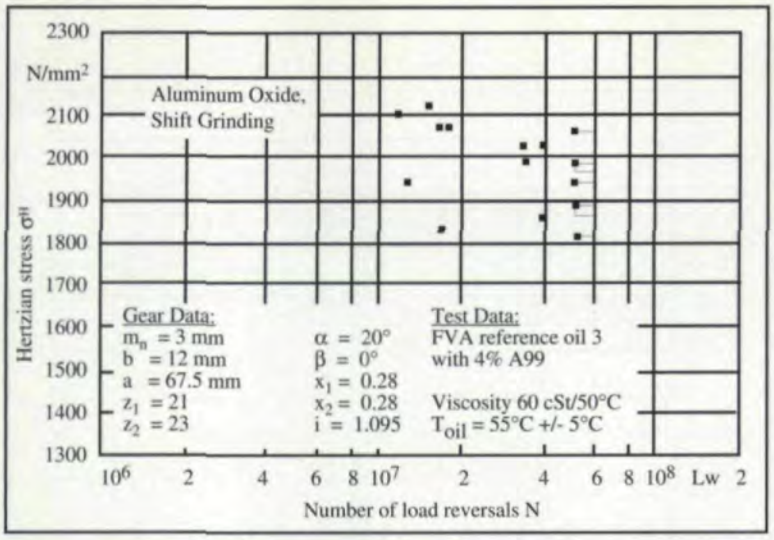

Fig. 5 — Endurable Hertzian face stress σ_H of case hardened gears (shift grinding aluminum oxide, Variant 111).

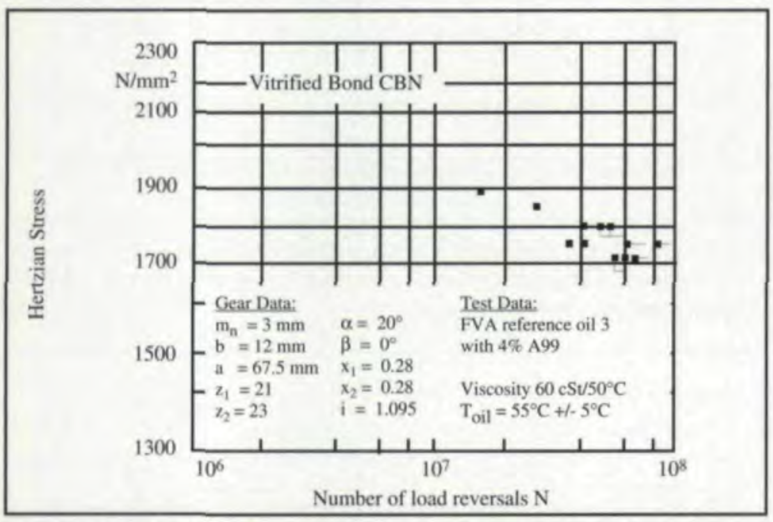

Fig. 6 — Endurable Hertzian face stress σ_H of case hardened gears (newly dressed vitrified bond CBN wheel, Variant 46).

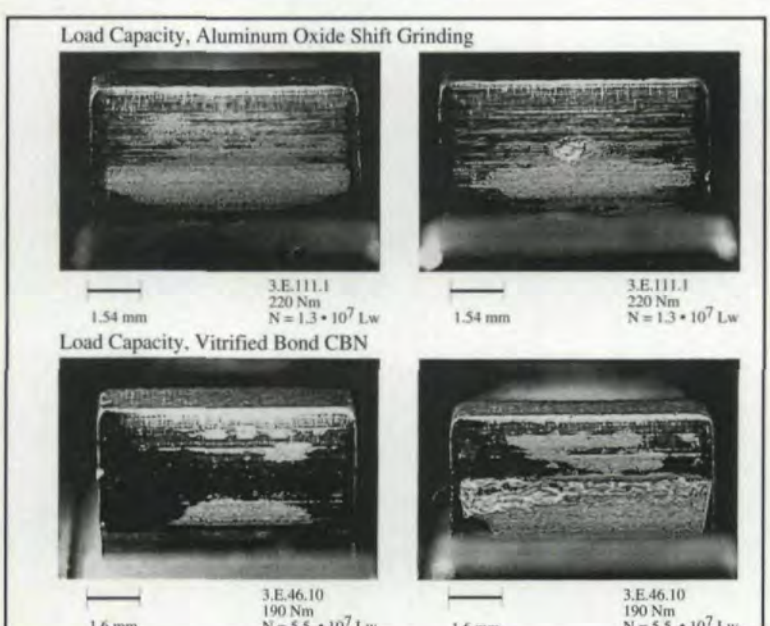

Fig. 7 — Wear and pitting on aluminum oxide and CBN ground gears (Variants 111, 46).

tangential stresses. These, in turn, can lead to damage to the material sub-surface zones. These processes could favor pitting.

No Increase in Tooth Face Load Capacity

Wöhler graphs were determined on a 3-shaft bracing test rig to analyze the face load capacity. On this test fixture a test pinion was meshed with two gears. The center distance was a = 67.5 mm. The maximum torque was 270 Nm. The amount of the load was varied by using the stair-step method (Ref. 8).

These limits were used as the basis for the wear criterion for pitting, depending on how the wear developed: failure of the gear at an individual tooth wear of 4% of the active tooth face, or failure of the gear at a total face wear of 1% of the entire active tooth face (Ref. 8).

The gears were continuously monitored while running, and the beginning and progress of the pitting was recorded. The results are presented in the form of a Wöhler diagram.

Fig. 5 shows the endurable Hertzian face stress σ_H during the running test (shift grinding with aluminum oxide, Variant 111). The torque of the gears was between *190* Nm (σ_H = 1712 N/mm^2) and a maximum of 267 Nm (σ_H = 2030 N/mm^2). Pitting occurred on the pinion and gear during the running.

After evaluation using the aforementioned criteria, a continuously endurable Hertzian face stress σ_H = 1750 N/mm^2 was established. At higher torques test gears could be found which did not reach the failure criteria after achieving the endurance strength limit of 5 x 10^7 load reversals, but there is insufficient empirically verified data available to allow one to specify higher continuously endurable Hertzian face stress with sufficient safety. Because of the considerable variation of the measured values, it is not possible to draw a suitable Wöhler line on the diagram.

Fig. 6 shows the endurable Hertzian face stress for the vitrified bond CBN variant with a newly dressed grinding wheel (Variant 46). In this case the torque of the gears was between 190 Nm (σ_H = 1712 N/mm^2) and a maximum of 230 Nm (σ_H = 1884 N/mm^2). Because the measured values show a considerable variation for this variant, no Wöhler line is drawn on the diagram. In this case a continuously endurable Hertzian face stress of approximately 1750 N/mm^2 was determined. Unlike the case of the aluminum oxide variant, fewer gears were found that passed the test without reaching the failure criteria at higher torque.

Pitting frequently occurred as mini-pitting in the form of striations in the range of gray discoloration which appeared as spots all over the entire face of the tooth (Fig. 7). With aluminum oxide ground gears, on the other hand, the gray spots appeared mainly in the negative slip area below the pitch circle. The results of the tests show no improvement in tooth face load capacity of the CBN ground gears compared with the aluminum oxide ground variants.

The main reason is to be found in the shallow depth that is influenced by the residual compressive stresses, which cannot affect the specific stress on the tooth faces in the lower material depths.

Review of Results

The results of the tests are summarized in Table II. High residual compressive stresses were found in the surface zone for CBN ground gears during measurement of the residual stress. These values were, however, found only on the surface or to a depth of approximately 10 µm. The deviations in the profile form, which were regarded as an indication of wear relative to the running time, were highest for the aluminum oxide ground variants, with a depth of 20 µm.

The aluminum oxide and CBN variants showed a different pattern with regard to the occurrence of gray discoloration. With the aluminum oxide ground gears a band of gray discoloration always occurred below the pitch circle. With the galvanically plated CBN variant, on the other hand, the gray discoloration was unevenly distributed (in spots) over the surface of the tooth face, because the surface structure was also not uniform and was interrupted by striations. The vitrified bond CBN variant showed a frequent occurrence of mini-pitting in the form of striations in the area of the gray discoloration.

With the exception of the aluminum oxide variant using shift grinding, the photographs of the structure for all other variants showed individual areas of rehardening to a maximum depth of about 2 µm (galvanically plated CBN, vitrified bond CBN, used wheels/newly dressed wheels) and approximately 8 µm for aluminum oxide multi-pass grinding. No adverse effects on the face load capacity could be found during the test because of the isolated occurrences on the face.

The average roughness depth R_z for the aluminum oxide variant was almost the same — approximately 3.86 µm (aluminum oxide multi-pass grinding) and 3.96 µm (aluminum oxide shift grinding). The values for the CBN ground variant were R_z = 2.17 µm (galvanically plated CBN), R_z = 2.39 µm (vitrified bond CBN, used wheel) and R_z = 2.28 µm (vitrified bond CBN, newly dressed wheel). These values are distinctly lower because of the surface topography of the CBN wheel and the favorable grinding parameters.

Table II — Summary of Results Showing Residual Stress Profile, Wear Pattern and Load Capacity of the Gear Variants.

Grinding Method	Residual Stresses (N/mm^2)	Affected Depth (µm)	Profile Deviation (Wear) µm	Gray Discoloration	Surface Zone (Re-Hardened Zones)	Average Roughness Depth R_Z	Face Load Capacity (n/mm^2)
Aluminum Oxide (Multi-Pass Grinding)	-260 (ax.) -400 (tg.)	Surface (residual stresses increase to about -300 N/mm^2 at depths > 0.01mm)	—	—	Isolated re-hardened zones, maximum depth approx. 8µm	Appx. 3.86 µm	—
Aluminum Oxide (Shift Grinding)	-260 (ax.) -400 (tg.)	Surface (residual stresses increase to about -300 N/mm^2 at depths > 0.01 mm)	Final state approximately 20 µm maximum	Gray discoloration occurring in band below pitch circle	Martensitic surface structure without influence from grinding process	Apprx. 3.96 µm	$\sigma_H = 1{,}750$
Galvanically Plated CBN	-500 (ax.) -950 (tg.)	In the surface zone down to 10 µm (values drop to about -200 N/mm^2 at depths > 0.01 mm)	Final state approximately 7 µm maximum	Irregular occurrence of gray discoloration	Isolated re-hardened zones, maximum depth approx. 2 µm	Apprx. 2.17 µm	—
Vitrified Bond CBN (Used Wheel)	-500 (ax.) -1,000 (tg.)	Surface (values drop to about -300 N/mm^2 at depths > 0.01 mm)	—	—	Isolated re-hardened zones, maximum depth approx. 2 µm	Apprx. 2.34 µm	—
Vitrified Bond CBN	-300 (ax.) -400 (tg.)	Surface (values drop to about -300 N/mm^2 at depths > 0.01 mm)	Final state approximately 14 µm maximum	Mini-pitting	Isolated re-hardened zones, maximum depth approx. 2 µm	Apprx. 2.28 µm	$\sigma_H = 1{,}750$

The investigations of the face load capacity showed that gears ground with vitrified bond CBN wheels reached the stress level of gears ground with aluminum oxide wheels, but by no means exceeded them. The favorable residual compressive stresses and improved roughness did not affect the permanent load capacity of the gears, because the depth to which the residual compressive stresses penetrate was not sufficient to reach the maximum stresses due to the Hertzian stress.

Summary

These investigations examined the influence of the grinding material (aluminum oxide, CBN) on the residual stress and face load capacity of case-hardened spur gears after continuous generating grinding. The CBN grinding technique promises a favorable surface zone influence in the form of high residual compressive stresses because of the better thermal conductivity of the CBN abrasive. Such residual compressive stresses can, in principle, improve the wear characteristics of the tooth face surface.

The test showed that the surface zone is not negatively influenced by the particular grinding method or grinding abrasive for any of the variants ground. The measurements of the residual stress for the CBN variants showed high residual compressive stresses in the zone close to the surface. These values were, however, only present in an extremely small band from the surface (approximately 10 µm for the galvanically plated CBN variant). The residual compressive stresses on the surface in the case of the aluminum oxide variants was approximately -260 N/mm^2 (axial) and -400 N/mm^2 (tangential). For the CBN variants it was approximately -500 N/mm^2 (axial) and -1000 N/mm^2 (tangential). At depths exceeding 0.01 mm these values dropped rapidly to about -300 N/mm^2.

The wear test of the aluminum oxide variants showed an increasing loss of material, depending upon the running time, below the pitch circle in the negative slip area. In contrast to this, the CBN variants showed an irregular gray discoloration over the complete tooth face. This can be explained by the different initial conditions of the surface structure. The average roughness depth R_Z is smaller (2.0 to 2.3 µm) on all CBN variants than on the aluminum oxide ground gears (3.9 to 4.0 µm). The reason for this may be the different grinding parameters and the surface topography of the CBN grinding wheel.

The aluminum oxide ground reference variant was produced under commercial production conditions, while the CBN variant ground for the tooth face load capacity tests used smaller infeed amounts and lower grinding wheel speeds with the best process selected for with regard to the minimum surface zone influence.

The continuously endurable tooth contact stress for both the aluminum oxide (shift grinding) variant and the vitrified bond CBN variant is at maximum 1750 N/mm^2.

No improvement in the tooth face load capacity could be found for the CBN ground gears even under the most favorable technological conditions. CBN grinding under commercial production conditions, therefore, does not point toward any significant improvement in the load capacity as described in Ref. 3. ■

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